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1. REPORT DATE (DD-MM-YYYY) 20-10-2012		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1-Sep-2005 - 31-Dec-2010	
4. TITLE AND SUBTITLE Two-dimensional arrays of neutral atom quantum gates				5a. CONTRACT NUMBER W911NF-05-1-0492	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 411359	
6. AUTHORS Mark Saffman				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Wisconsin - Madison The Board of Regents of the University of Wisconsin System Suite 6401 Madison, WI 53715 -1218				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211				10. SPONSOR/MONITOR'S ACRONYM(S) ARO	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) 47949-PH-QC.27	
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT Under this project a two-qubit entangling gate was developed and demonstrated. Two neutral atom qubits held in optical traps 9 microns apart were entangled using a Rydberg blockade gate and the threshold for deterministic entanglement was passed. The previous report covered the period 1-Aug-2009 - 31-Jul-2010. Since 1-Aug-2010 this research has continued under the IARPA MQCO program.					
15. SUBJECT TERMS quantum computing, Rydberg atoms, entanglement					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Mark Saffman
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 608-265-5601

## Report Title

Two-dimensional arrays of neutral atom quantum gates

### ABSTRACT

Under this project a two-qubit entangling gate was developed and demonstrated. Two neutral atom qubits held in optical traps 9 microns apart were entangled using a Rydberg blockade gate and the threshold for deterministic entanglement was passed. The previous report covered the period 1-Aug-2009 - 31-Jul-2010. Since 1-Aug-2010 this research has continued under the IARPA MQCO program.

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**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

ReceivedPaper

- 03/11/2010 1.00 M. Saffman. Efficient Multiparticle Entanglement via Asymmetric Rydberg Blockade, , (10 2005): . doi:
- 10/19/2012 5.00 C. Knoernschild, X. L. Zhang, L. Isenhowe, A. T. Gill, F. P. Lu, M. Saffman, J. Kim. Independent individual addressing of multiple neutral atom qubits with a micromirror-based beam steering system, Applied Physics Letters, (09 2010): 134101. doi: 10.1063/1.3494526
- 10/19/2012 4.00 L. Isenhowe, X. Zhang, A. Gill, T. Walker, M. Saffman. Deterministic entanglement of two neutral atoms via Rydberg blockade, Physical Review A, (09 2010): 0. doi: 10.1103/PhysRevA.82.030306
- 10/19/2012 6.00 L. Isenhowe, W. Williams, A. Dally, M. Saffman. Atom trapping in an interferometrically generated bottle beam trap, Optics Letters, (04 2009): 0. doi: 10.1364/OL.34.001159
- 10/19/2012 7.00 M. Saffman, D. Oblak, J. Appel, E. Polzik. Spin squeezing of atomic ensembles by multicolor quantum nondemolition measurements, Physical Review A, (02 2009): 0. doi: 10.1103/PhysRevA.79.023831
- 10/19/2012 8.00 E. Urban, T. A. Johnson, T. Henage, L. Isenhowe, D. D. Yavuz, T. G. Walker, M. Saffman. Observation of Rydberg blockade between two atoms, Nature Physics, (01 2009): 0. doi: 10.1038/nphys1178
- 10/19/2012 9.00 K. Mølmer, M. Saffman. Scaling the neutral-atom Rydberg gate quantum computer by collective encoding in holmium atoms, Physical Review A, (07 2008): 0. doi: 10.1103/PhysRevA.78.012336
- 10/19/2012 10.00 M Saffman, X L Zhang, A T Gill, L Isenhowe, T G Walker. Rydberg state mediated quantum gates and entanglement of pairs of neutral atoms, Journal of Physics: Conference Series, (01 2011): 0. doi: 10.1088/1742-6596/264/1/012023
- 10/19/2012 11.00 Anne Nielsen, Klaus Mølmer. Topological matter with collective encoding and Rydberg blockade, Physical Review A, (11 2010): 0. doi: 10.1103/PhysRevA.82.052326
- 10/19/2012 12.00 Klaus Mølmer, Anne E. B. Nielsen. Deterministic multimode photonic device for quantum-information processing, Physical Review A, (04 2010): 0. doi: 10.1103/PhysRevA.81.043822
- 10/19/2012 13.00 Sangtaek Kim, Robert R. Mcleod, M. Saffman, Kelvin H. Wagner. Doppler-free, multiwavelength acousto-optic deflector for two-photon addressing arrays of Rb atoms in a quantum information processor, Applied Optics, (04 2008): 0. doi: 10.1364/AO.47.001816
- 10/19/2012 14.00 Thad Walker, M. Saffman. Consequences of Zeeman degeneracy for the van der Waals blockade between Rydberg atoms, Physical Review A, (03 2008): 0. doi: 10.1103/PhysRevA.77.032723
- 10/19/2012 20.00 T. Johnson, E. Urban, T. Henage, L. Isenhowe, D. Yavuz, T. Walker, M. Saffman. Rabi Oscillations between Ground and Rydberg States with Dipole-Dipole Atomic Interactions, Physical Review Letters, (3 2008): 0. doi: 10.1103/PhysRevLett.100.113003
- 10/19/2012 16.00 L. Pedersen, M. Saffman, E. Brion, K. Mølmer. Error Correction in Ensemble Registers for Quantum Repeaters and Quantum Computers, Physical Review Letters, (3 2008): 0. doi: 10.1103/PhysRevLett.100.110506
- 10/19/2012 17.00 E. Brion, K. Mølmer, M. Saffman. Quantum Computing with Collective Ensembles of Multilevel Systems, Physical Review Letters, (12 2007): 0. doi: 10.1103/PhysRevLett.99.260501

10/19/2012	18.00	E. Brion, L. Pedersen, K. Mølmer, S. Chutia, M. Saffman. Universal quantum computation in a neutral-atom decoherence-free subspace, Physical Review A, (3 2007): 0. doi: 10.1103/PhysRevA.75.032328
10/19/2012	19.00	D. Yavuz, P. Kulatunga, E. Urban, T. Johnson, N. Proite, T. Henage, T. Walker, M. Saffman. Fast Ground State Manipulation of Neutral Atoms in Microscopic Optical Traps, Physical Review Letters, (2 2006): 0. doi: 10.1103/PhysRevLett.96.063001
10/19/2012	21.00	L H Pedersen, K Mølmer, E Brion. Implementing a neutral atom Rydberg gate without populating the Rydberg state, Journal of Physics B: Atomic, Molecular and Optical Physics, (05 2007): 0. doi: 10.1088/0953-4075/40/9/S09
10/19/2012	22.00	E Brion, L H Pedersen, K Mølmer. Adiabatic elimination in a lambda system, Journal of Physics A: Mathematical and Theoretical, (02 2007): 0. doi: 10.1088/1751-8113/40/5/011
10/19/2012	23.00	Line Hjortshøj Pedersen, Niels Martin Møller, Klaus Mølmer. Fidelity of quantum operations, Physics Letters A, (7 2007): 0. doi: 10.1016/j.physleta.2007.02.069
10/19/2012	24.00	E. Brion, A. Mouritzen, K. Mølmer. Conditional dynamics induced by new configurations for Rydberg dipole-dipole interactions, Physical Review A, (8 2007): 0. doi: 10.1103/PhysRevA.76.022334
10/19/2012	25.00	T. Walker, K. Mølmer, M. Saffman. Quantum information with Rydberg atoms, Reviews of Modern Physics, (8 2010): 0. doi: 10.1103/RevModPhys.82.2313
10/19/2012	26.00	L. Isenhower, E. Urban, X. L. Zhang, A. T. Gill, T. Henage, T. A. Johnson, T. G. Walker, M. Saffman. Demonstration of a Neutral Atom Controlled-NOT Quantum Gate, Physical Review Letters, (01 2010): 0. doi: 10.1103/PhysRevLett.104.010503

**TOTAL:           23**

Number of Papers published in peer-reviewed journals:

**(b) Papers published in non-peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

Number of Papers published in non peer-reviewed journals:

**(c) Presentations**

Quantum gates and collective qubits in strongly interacting atomic ensembles, (Workshop on Quantum Information Processing and Nanoscale Systems, NSF, Washington D.C., September 11, 2007)

Excitation and interaction of Rydberg atoms for quantum bits and quantum registers (PQE-2008, Physics of Quantum Electronics, Snowbird, January 8, 2008)

Experimental progress in coherent control of Rydberg atoms  
(workshop on Rydberg Excited Atoms, Sandbjerg, Denmark, May 14-16, 2008)

Controlling neutral atom quantum states by Rydberg interactions  
(Midwest cold atom workshop, Argonne National Laboratory, Chicago, November 15, 2008)

Observation of two-atom Rydberg blockade, (DAMOP, Williamsburg, May 23, 2009)

Demonstration of a neutral atom quantum gate and perspectives on scalability, (Aspen workshop on Quantum Simulation/Computation with Cold Atoms and Molecules June 10, 2009)

Quantum information processing with Rydberg atoms, 30th CNLS Annual Conference - Complexity and Disorder at Ultra-Low Temperatures (June 21-25, 2010)

EU Quantum Information Processing Open Day, (July 7, 2010 Oxford)

Rydberg quantum gate, International Conference on Atomic Physics, ICAP , Cairns, (July 2010)

Quantum information with Rydberg atoms  
Rydberg Workshop, Dresden, (September 2010)

Rydberg enabled quantum information processing,  
Optical Society of America annual meeting, Frontiers in Optics/Laser Science, Rochester, (October 2010).

Rydberg gates, Rydberg Workshop, Recife, (November 2010)

**Number of Presentations:** 12.00

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**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

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**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Received      Paper

**TOTAL:**

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

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**(d) Manuscripts**

Received      Paper

03/11/2010	2.00	L. Isenhowe, E. Urban, X. Zhang, A. Gill, T. Henage, T. Hohnson, T. Walker, M. Saffman. Demonstration of a neutral atom controlled-NOT quantum gate, (10 2009)
03/11/2010	3.00	M. Saffman, T. Walker. Quantum information with Rydberg atoms, (09 2009)

**TOTAL:      2**

**Number of Manuscripts:**

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**Books**

Received      Paper

**TOTAL:**

**Patents Submitted**

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**Patents Awarded**

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**Awards**

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M. Saffman, 2008 Fellow American Physical Society

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### Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Siyuan Zhang	0.40	
Alex Gill	0.50	
Larry Isenhowe	0.50	
Kara Maller	0.25	
Erich Urban	0.50	
Todd Johnson	0.50	
Alex Gill	0.50	
<b>FTE Equivalent:</b>	<b>3.15</b>	
<b>Total Number:</b>	<b>7</b>	

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### Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	
Xianli Zhang	0.50	
Larry Isenhowe	0.10	
Deniz Yavuz	0.40	
<b>FTE Equivalent:</b>	<b>1.00</b>	
<b>Total Number:</b>	<b>3</b>	

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### Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Mark Saffman	0.10	
Thad Walker	0.10	
Klaus Moelmer	0.05	
<b>FTE Equivalent:</b>	<b>0.25</b>	
<b>Total Number:</b>	<b>3</b>	

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### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Benjamin Broerman	0.10	Physics
Jake Covey	0.10	Physics
Antoine Martin	0.10	Physics
Kevin Christie	0.10	Physics
<b>FTE Equivalent:</b>	<b>0.40</b>	
<b>Total Number:</b>	<b>4</b>	

### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 3.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 3.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 3.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 3.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... 0.00

### Names of Personnel receiving masters degrees

NAME

Thomas Henage

**Total Number:**

1

### Names of personnel receiving PhDs

NAME

Larry Isenhower

Todd Johnson

Erich Urban

**Total Number:**

3

### Names of other research staff

NAME

PERCENT SUPPORTED

**FTE Equivalent:**

**Total Number:**

### Sub Contractors (DD882)

### Inventions (DD882)



**Scientific Progress**

See Attachment

**Technology Transfer**

## **QCCM - Two-dimensional arrays of neutral atom quantum gates**

**Principal Investigators:** Mark Saffman, Thad G. Walker, University of Wisconsin Madison; Klaus Mølmer, University of Aarhus, Denmark

**Final Report for 09/01/2005 to 12/31/2010**

### **Project Description:**

The major project goal was to demonstrate quantum logic gates with neutral atoms in a two dimensional array of optically defined trapping sites. A small 2D array of 6 trapped atom sites was demonstrated and a CNOT gate was demonstrated between a pair of trapped atoms in neighboring sites (Isenhower et al. PRL 2010). It was also shown that the CNOT gate could be used for deterministic entanglement of a pair of atoms (Zhang et al. PRA 2010). Detailed reports on the experimental methods used and technical approach can be found in the previous interim reports from this project.

A review of the use of Rydberg atoms for quantum information was also published by us in 2010 (Saffman, et al. Rev. Mod. Phys. 2010). The experimental and theoretical progress of the last five years by our group, and many others worldwide, is presented in the review.

The Madison CNOT experiment was the first demonstration of a two-qubit entangling gate with one pair of neutral atom qubits. The Rydberg blockade mechanism which was used for the gate is attractive for scaling to a larger array of neutral atom qubits since the long range nature of the interaction can be used for entanglement beyond nearest neighbor qubits. Starting in August 2010 work commenced on building a 2D neutral atom array for quantum computing experiments. The decision was also made to switch from Rb to Cs atoms. The reason being that Cs provides a better match to available medium power laser wavelengths for fast excitation of Rydberg states.